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DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
MATERIALS RESEARCH LABORATORIES
MELBOURNE, VICTORIA

REPORT

MRL-R-979

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DETERMINATION OF SHOCK INITIATION AND DETONATION
CHARACTERISTICS OF PE4 IN PROOF TEST GEOMETRIES

M.C. Chick and L.A. Learmonth

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Various shock initiation and detonation properties relevant to the detonation proof testing of PE4 are reported and used to assess the results of a survey of over 450 proof tests on production PE4 for the five year period up to 1981. Our conclusions from the investigation include the following: high moisture content can cause failures, large variations in plasticizer content (up to double) do not cause failures, voids in the PE4 adjacent to and under the detonator do not cause failure, a void across the complete diameter of the PE4 test sample adjacent to the steel plate can cause partial failures, the L2A1 detonator has more than sufficient power to detonate the PE4, full detonation is achieved within the PE4 and the test geometry is several orders of magnitude greater than the critical diameter to support detonation.

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DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-R-979	AR-004-345	Unclassified

TITLE

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Characteristics of PE4 in Proof Test Geometries

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REPORT DATE

November, 1985

TASK NO.

ARM 94/114

SPONSOR

ARMY

FILE NO.

G6/4/8-3124

REFERENCES

9

PAGES

18

CLASSIFICATION/LIMITATION REVIEW DATE

CLASSIFICATION/RELEASE AUTHORITY

Superintendent, MRL
Physical Chemistry Division

SECONDARY DISTRIBUTION

Approved for Public Release

ANNOUNCEMENT

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KEYWORDS

Plastic Explosives,
RDX;

Sensitivity;
Shock;

Detonation (Australia)
PE4

COSATI GROUPS

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Various shock initiation and detonation properties relevant to the detonation proof testing of PE4 are reported and used to assess the results of a survey of over 450 proof tests on production PE4 for the five year period up to 1981. Our conclusions from the investigation include: the following: high moisture content can cause failures; large variations in plasticizer content (up to double) do not cause failures; voids in the PE4 adjacent to and under the detonator do not cause failure; a void across the complete diameter of the PE4 test sample adjacent to the steel plate can cause partial failures; the L2A1 detonator has more than sufficient power to detonate the PE4; full detonation is achieved within the PE4 and the test geometry is several orders of magnitude greater than the critical diameter to support detonation.

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DETERMINATION OF SHOCK INITIATION AND DETONATION

CHARACTERISTICS OF PE4 IN PROOF TEST GEOMETRIES

1. INTRODUCTION

PE4 is a white, soft plastic explosive, originally formulated in the United Kingdom and in service in Australia. It is the standard service explosive for demolition and Explosive Ordnance Disposal (EOD). The basic ingredients are:

RDX grade B (boiled and milled)	88%
Plasticizer (PE4 grease)	11%
Pentaerythritol di-oleate, PEDO	1%

Production is undertaken at the Albion Explosives Factory and the detonation proof test is carried out according to Australian Proof Requirement 818/1 by the 3rd Army Quality Assurance Unit (3 AQAU).

During 1979-80 some samples of PE4 did not satisfy the penetration requirements of the detonation proof test. As a consequence 3 AQAU requested the Materials Research Laboratories to investigate the possible causes of the failures.

The detonation proof test essentially assesses the shock sensitivity of the PE4 sample under test. Thus our investigation was carried out in two phases. In the first phase we conducted a survey of the detonation proof testing and chemical analysis results from PE4 produced over the five year period up to 1981. The second phase consisted of a study of the shock and detonation characteristics of PE4: this included an examination of the effects of various types of voids incorporated into several positions of the PE4 charge of the detonation proof test.

This paper presents the results of the investigation and draws conclusions on some factors that may be important in the detonation proof testing and production of PE4.

2. DESCRIPTION OF PE4 DETONATION PROOF TEST

The detonation proof test arrangement is shown in Fig. 1. The detonator is placed in a cylindrical hole formed along the axis of the PE4 charge by an appropriate tool. This results in about two thirds of the length of the tetryl (CE) charge in the detonator being located within the PE4. This produces an effective arrangement for the initiation of the test sample. The tetryl pellets, of mass 0.25 g each, have a density of 1.591 Mg/m³ and are pressed prior to filling into the aluminium case of the detonator. The pellets have a radius of 3.8 mm and a total length of 19 mm.

The components for the detonation proof tests were supplied by the Army Inspection Service. The PE4 was supplied from 2 production incorporations (371 and 562) made by Albion Explosives Factory. Both materials passed detonation proof and chemical analysis was within specification. In particular the volatile matter contents of 0.08 and 0.09% w/w were below the recommended maximum of 0.10% w/w. Several density determinations gave a mean value of 1.59 ± 0.01 Mg/m³. The density of UK produced PE4 is reported as 1.60 Mg/m³ [1].

A successful test requires that a cylinder of PE4 25.4 mm diameter by 25.4 mm long when initiated by the L2A1 detonator positioned half way down the charge completely perforates a 6.4 mm thick greased steel plate placed on a 100 mm thick bed of sand. Perforation is considered completed when the circular steel scab is wholly detached from the plate or is only attached lightly enough to be detached with the fingers. For an incorporation to pass proof, 3 representative samples must perforate the plate correctly. If one charge fails the test, then the incorporation must pass a reproof of 6 successful firings. Any incorporation that fails the reproof or exhibits more than 1 charge failing the first proof, is rejected.

Examination of the detonation proof test geometry in Fig. 1 shows that the test essentially records the ability of the tetryl booster pellets to shock initiate the PE4 sample through the thin aluminium case of the L2A1 detonator. Thus it is a shock sensitivity test where the tetryl pellets act as the donor charge. Therefore the shock initiation and detonation characteristics of the PE4 test sample are important in determining the results of the proof.

The proof procedure is described in Australian Proof Requirement 818/1. The available literature contains little information on either the detonation proof test or on the shock sensitivity characteristics of PE4.

3. SURVEY OF PRODUCTION PE4 PROOF TESTING AND CHEMICAL ANALYSIS

The survey examined the results of detonation proof testing and the associated chemical analysis of all PE4 produced over the 5 year period up to late 1981.

A production run of PE4 is termed an incorporation which is made up from mixing together about 15 separate batches of RDX/plasticizer with the PEDO grease. About 1100 sticks of PE4 are made from each incorporation of which 2 are used for chemical analysis and 1 is used for detonation proof testing.

During the survey period 7 incorporations from a total production of 454 incorporations failed first proof (1.5%). All except 1 incorporation passed reproof. Thus put another way, since 3 rounds are fired per incorporation and 6 rounds are required to be fired for reproof, a total of 12 rounds failed from 1404 firings (0.85%).

The dates and incorporation reference numbers of the samples which failed the first proof are given in Table 1. These data show that the failures were not spread over the complete time scale surveyed but grouped into 3 periods of 1 or 2 days each. No samples failed proof over the latter 18 months of the examination period during which 310 incorporations were tested. Thus a general shift in either the preparation of the PE4 or in the proof testing procedure is not supported.

Three of the 7 incorporations that failed first proof had volatile matter contents greater than the 0.10% w/w recommended maximum of the specification (see Table 1). During this period Albion Explosives Factory passed material with a volatile content of up to 0.15% w/w. Further, the incorporation with the highest volatile content (0.15% w/w) was the only one in which all 3 samples failed to puncture the witness plate. Some incorporations with volatile matter contents in the range 0.10% to 0.15% w/w passed the detonation proof test.

The incorporations listed in Table 1 complied with the chemical analysis specification in all other respects.

TABLE 1

Summary of PE4 samples that failed detonation proof

Incorporation Reference Number	Date	Volatile Matter %
237	19- 1-78	0.12
263	26- 3-79	0.07
265	26- 3-79	0.09
328	13-10-80	0.13
329	13-10-80	0.15
332	14-10-80	0.08
337	14-10-80	0.08

4. STUDY OF PE4 INITIATION AND DETONATION CHARACTERISTICS

As explained in Section 2 the detonation proof test essentially assesses the shock sensitivity of the PE4 sample. If it is assumed that the L2A1 detonator functions correctly then the important characteristics of the explosive components of the test are; the sensitivity of the PE4 to shock, the relative magnitude of the shock transmitted from the tetryl pellets to the PE4 compared with the minimum shock required to initiate the PE4, the attainment of full detonation in PE4, the effect of PE4 volatile matter and plasticizer content on its shock sensitivity, the critical cross section size of PE4 to sustain steady detonation and the effects of any voids in the PE4 on the success of the shock transfer process to obtain detonation. Each of these factors has been examined.

4.1 Shock Sensitivity Characteristics of PE4

The shock sensitivity of PE4 was determined on the MRL small scale gap test [2], see Fig. 2. The test consists of a standard explosive donor charge separated from the explosive under test by an adjustable brass gap which acts to attenuate the shock from the donor. The brass gap is varied in a prescribed manner to determine the critical thickness which gives a 50% probability of detonation. Usually 20-25 shots are fired per determination. The critical gap thickness is a measure of the shock sensitivity of the test explosive.

The MRL small scale gap sensitivity of PE4 of 0.51 mm (mean of 3 determinations) compares to a value of 2.86 mm for pressed tetryl at 1.48 Mg/m^3 . The reported values of PE4 and pressed tetryl (density 1.50 Mg/m^3) produced and tested in the UK are 1.6 mm and 7.33 mm respectively [3]. Thus the MRL PE4 value is consistent with the pattern of results from the two tests. The higher values from the UK gap test compared to the MRL test are attributed to differences in the test components.

An assessment has been made of the relative magnitude of the shock pressure transmitted to the PE4 from the detonating tetryl in the L2A1 detonator to the minimum pressure required to initiate the PE4. The critical pressure to initiate PE4 has not been determined. However, a value of 2.2 GPa has been reported for the initiation of Composition C4 from the Naval Surface Weapons Centre (NSWC) calibrated gap test [4]. Composition C4 is a brown puttylike solid, density 1.56 Mg/m^3 , containing 91% RDX and 9% inert (Di(2-ethyl hexyl)sebacate 5.3%, Polyisobutylene 2.1%, motor oil 1.6%). Thus like PE4, Composition C4 is a plastic explosive and has a similar composition and density. Both explosives also appear in a similar position relative to other explosives in the order of gap test sensitivities as measured on the MRL [2] and NSWC [4] tests. Therefore for the purposes of this assessment both explosives will be assumed to have a similar critical initiation pressure.

The shock pressure transmitted from the detonating tetryl to the PE4 was estimated using the impedance matching technique. This is illustrated in Fig. 3 and relevant data are listed in Table 2. The shock Hugoniot has not been determined for unreacted PE4 and the data for PBX9407 (RDX/EXON 461, 94/6, density 1.60 Mg/m^3) was taken as a substitute [5]. The substitute was selected on the basis of being the closest explosive to PE4 in terms of density and composition for which shock Hugoniot data was available.

TABLE 2

Data used for Impedance Matching Estimate of Shock Transmitted from L2A1 Detonator to PE4 Simulant

Material	Physical Characteristics	Shock Relationship
Tetryl Donor from L2A1 Detonator	Density = 1.591 Mg/m^3 Radius = 2.8 mm Length = 19 mm	Ideal $P_{CJ} = 21.9 \text{ GPa}$ Data from Reference [6]
Aluminium Case of L2A1 Detonator	Thickness 0.45 mm Density = 2.78 Mg/m^3	$U_s = 5.37 + 1.29 U_p^*$
PE4	Density 1.593 Mg/m^3 Radius 12.8 mm Thickness 12.8 mm	$U_s = 1.35 + 1.94 U_p^*$ (PBX 9407 Data taken as Simulant for PE4)

* Reference [5]

The pressure transferred from the detonating tetryl to the aluminium case of the detonator, P_1 , (see Fig. 3) was determined by the intersection of the shock Hugoniot for aluminium [5] with the Hugoniot for the detonation products of tetryl since the conservation conditions require that the pressure and particle velocity be identical across the interface. As the radius of the tetryl charge (2.8 mm) was several orders of magnitude greater than the 0.45 mm thickness of the aluminium case it was assumed that the peak pressure, P_1 , of the shock propagating through the aluminium was not reduced by rarefactions. The pressure transmitted to the PE4 simulant (PBX 9407) from the aluminium case was then obtained by the intersection of the reflected aluminium Hugoniot about P_1 with the Hugoniot for the unreacted PE4 simulant. The value of the shock pressure in the PE4 simulant, P_2 , is about 14 GPa which is several times greater than the estimated minimum pressure to cause detonation of about 2.2 GPa. Hence the build-up to detonation will be rapid. This supports the finding in Section 4.3 that large distortions in the physical arrangement of the test at the detonator/PE4 interface did not cause failures.

4.2 Effect of High Volatile Matter Content on Shock Sensitivity of PE4

The survey of proof testing results and chemical analysis (see Section 3 and Table 1) showed that the samples that failed detonation proof testing had a high incidence of volatile matter content (moisture) that was greater than the recommended maximum of the specification. Rudram et al [7] carried out an extensive investigation on the effect of volatile matter content on detonation proof results in PE4, with particular emphasis on determining the regions where either intermittent or consistent detonation proof failures occurred. Batches of PE4 were prepared and dried gradually in a small incorporator. Samples were taken at intervals for volatile matter determination and detonation proof testing.

The study showed there was a relationship between high volatile matter content and detonation proof test failures and concluded, "a residual volatile matter of 0.10 to 0.15% w/w is a potential cause of detonation failure and 0.30% or more is an almost certain cause of failure.

Thus the results from both the survey and the Rudram et al investigation suggest that at least some of the PE4 samples failed the detonation proof test as a result of high volatile matter contents.

The function of the small amount of volatile content (moisture) in markedly decreasing the sensitivity of the PE4 is not clear and may be associated with the moisture decreasing the shock impedance (density) mismatch in any voidage at the explosive surface. The effect is worthy of study but was considered to be outside the scope of the investigation.

4.3 Effect of Variation in Grease Content on Shock Sensitivity of PE4

The shock sensitivity of explosives is generally decreased by the addition of inerts such as grease and wax. Thus an uneven distribution of the plasticizer in PE4 may cause a variation in shock sensitivity and in the worse case be a potential cause of failures in the detonation proof test. This proposition has been investigated by proof testing and assessing the shock sensitivity of PE4 modified by the incorporation of two different amounts of extra plasticizer. The results are given in Table 3 and show a significant and progressive decrease in the shock sensitivity (as measured on the gap test) of the PE4 with increasing plasticizer content. However, all the compositions passed the proof test. This suggests that a variation in plasticizer content is not responsible for the observed failures, and further, that the proof test is quite insensitive to a large variation in the amount of plasticizer in the PE4. The results also demonstrate that the gap test is the more discriminating test. Presumably the function of the extra grease was to dilute the RDX and decrease the density of reaction sites (hot spots) formed in the initiation process. Consequently a stronger shock was required to produce detonation - in the gap test this was achieved by decreasing the brass barrier thickness.

TABLE 3

Effect of extra plasticizer on PE4 proof testing

Sample	Plasticizer Content, %	Density Mg/m ³	MRL Small Scale Gap Test Value		Detonation Proof Test
			M50% mm	L95% mm	
Control	11.0	1.59	0.45	0.43 and 0.46	Passed
1	15.04	1.49	0.36	0.35 and 0.38	Passed
2	19.1	1.48	0.32	0.30 and 0.33	Passed

4.4 Effect of Voids in PE4 on Detonation Proof Testing

The soft nature of PE4 raises the possibility of the introduction of voids from horizontal and vertical detonator movement and from the explosive not being in close contact with the steel plate.

A range of cylindrical air gaps was incorporated into the PE4 at the base of the detonator (see Fig. 4(a)). The air gap diameters were the same as the detonator and the thicknesses ranged from 1 mm up to the total removal of all PE4 from between the detonator and steel witness plate (12.7 mm). All firings gave clean perforations with a single scab and consequently passed proof. A series of firings was conducted with the detonators positioned in the PE4 and subsequently displaced from the vertical by a variety of angles up to 45° which is the maximum permissible by the geometry of the test components (see Fig. 4(b)). In this way a series of coupled voids was produced at the base and towards one side of the detonator. All experiments produced clean perforations with a single scab.

A test with a 5 mm thick air gap across the diameter of the PE4 sample adjacent to the steel plate (see Fig. 4(c)) produced a dent in the plate with no signs of perforation. The appearance of this circular dent with sharp edges and wash marks around the perimeter was quite different to the smooth surface of the indentation in the witness plate supplied by 3 AQAU as an example of a failure. A 5 mm gap represents a very large void, removing about 41% of the explosive in the region between the detonator and steel plate and may be considered most unlikely to occur. When the thickness of this type of void was reduced to 2 mm, 4 out of 5 firings produced steel witness plates with the characteristics of a partial; that is perforation occurred but with the scab firmly hinged to and bent back from the steel plate. These results were similar to the sample supplied by 3 AQAU as an example of a partial type of failure. The remaining shot in the series produced a clean perforation. The 2 mm void represents removing 16% of the

PE4 in the detonator-steel plate region. A firing with an indentation made by a thumb pressed into the PE4 adjacent to the steel plate produced a clean perforation with a single scab. Tests with triangular voids in the corner of the cardboard tube and steel plate produced clean perforations of the steel plate (see Fig. 4(d)).

A round fired with PE4 replaced by plasticine, an inert material of similar consistency and density to PE4, did not produce any indentation on the steel plate. This demonstrates that the detonator output was not capable of contributing towards the perforation of the plate. During the course of the experiments several conventional proof tests were conducted as a check of the procedure and components. All functioned correctly.

The results demonstrate that the proof test is capable of sustaining large distortions in the physical arrangement of the detonator/PE4 interface before a malfunction occurs. The successful firings with large voids at the base of the detonator suggests that PE4 initiation can occur through the wall of the detonator. The type of partial failure observed in the detonation proof tests of production PE4 appears to have been reproduced in 4 out of 5 tests by the incorporation of a 2 mm thick air gap across the full diameter of the PE4 sample adjacent to the steel witness plate.

4.5 Determination of PE4 Critical Dimensions for Stable Detonation

Explosive charges with dimensions less than a certain critical value will not support detonation and those charges whose geometry approaches the critical value can exhibit reduced detonation velocities and/or erratic behaviour. Thus in order to assess how the geometry of the PE4 in the detonation proof test compares to its critical cross section, the critical diameter and thickness have been estimated. All charges were initiated with an Exploding Wire Detonator (EBW).

The critical thickness was estimated by initiating the thick end of a 2° wedge of explosive 23 mm wide and 350 mm long. The charge was placed in intimate contact with a large steel witness block whose surface had been polished. The end of the detonation wash marks gave an estimate of the critical thickness. This method gives only an approximate value since the detonation will overdrive past the actual critical thickness and the steel support provides confinement on one side. The mean of 2 determinations was 1.1 mm. The critical diameter may be several times more than the critical thickness of an explosive slab since in the former case the quenching rarefactions can enter from all sides.

The critical diameter was estimated by firing cylindrical charges of PE4 with larger header dimensions to ensure reliable initiation. The cylinders were 140-200 mm long cased in thin plastic tubing. The far end was placed in intimate contact with a steel witness block to record whether propagating detonation or failure occurred. The results are given in Table 4 and give an estimated critical diameter of between 2.6 and 4.0 mm.

The critical dimensions of a rectangular cross section were also estimated in a similar manner. The results are listed in Table 4 and are similar to the cross section of the critical diameter.

These tests show that the diameter of the PE4 in the detonation proof test is about 6 to 8 times greater than the critical value and the diameter of the detonator is about twice the critical value. Thus the geometry of the test sample will allow the establishment of stable detonation and will not be responsible for erratic behaviour or failures.

TABLE 4

Critical cross sections of PE4 for stable detonation

Charge Dimensions mm	Result
5.4 diameter	Detonation
4.0 diameter	Detonation
4.0 diameter	Detonation
2.6 diameter	Failure
2.6 diameter	Failure
3 x 5	Detonation
3 x 4	Detonation
3 x 3.5	Detonation
2 x 2	Failure

4.6 Detonation Velocity of PE4 in Proof Test Geometries

The velocity of detonation of PE4 was determined in 25.4 mm diameter columns confined in cardboard tube using an automatic processing system developed at MRL [8]. These experiments were also used to assess whether full detonation had been achieved in the PE4 in the proof test following initiation by an L2A1 detonator.

Four firings were carried out each with 9 probes. Two rounds were fired with L2A1 detonators and two rounds with EBW detonators. Each probe consisted of two tightly stretched parallel wires at right angles to the axis of the column of PE4. Probes were positioned approximately 20 mm apart, except for one of the L2A1 initiated rounds in which the first 3 probes were 10 mm apart. The final positions of the probes were determined by radiography.

Although care was taken to minimise handling of the PE4, radiography of the filling did show voids due to separation within the PE4. Further, some of the probe wires were distorted and not normal to the axis of the charge. Both these factors may have had an effect on the results.

The detonation front shorted the probes and the pulses were recorded on a Biomation Type 6500 transient waveform recorder. The results were then automatically processed on a MF211 microcomputer.

The L2A1 detonator round showed that full detonation had been obtained within the first 10 mm of run. This suggests that the geometry of the PE4 proof test allows the attainment of detonation by the time the front reaches the interface with the steel plate.

The mean and standard deviation of the velocity of detonation for each of the charges are shown in Table 5. The overall mean of the 4 values for the PE4 at a density of 1.59 Mg/m^3 is 8027 m/s with a standard deviation of 180 m/s. This value compares to that calculated using the BKW computer code of 7882 m/s [9]. The calculated BKW detonation pressure is 24.7 GPa.

TABLE 5
Velocity of Detonation of PE4 at 1.59 Mg/m^3

Charge Reference	Velocity of Detonation	
	Mean, \bar{x} m/s	Standard Deviation, σ_n m/s
1 L2A1 Initiated	8064	166
2 EBW "	7945	195
3 L2A1	8013	190
4 EBW "	8086	168

Overall $\bar{x} = 8027 \text{ m/s}$, $\sigma_n = 180 \text{ m/s}$

5. CONCLUSIONS

1. The critical diameter, velocity of detonation and gap test sensitivity of PE4 have been determined.
2. With respect to failures in the PE4 detonation proof test the following conclusions may be drawn from the experiments and observations described in the report:

- a. 3 of the 7 incorporations that failed first proof had volatile matter contents greater than the 0.1% w/w required maximum. A UK investigation [7] concluded that a volatile matter content from 0.10% to 0.15% w/w is a potential cause of failure,
- b. The type of partial failure observed by 3 AQAU appears to have been reproduced (in 4 out of 5 firings) by the incorporation of a 2 mm thick air gap across the full diameter of the PE4 sample adjacent to the steel witness plate. However, this may be considered unlikely to occur in practice.
- c. Large distortions in the physical arrangement of the test at the detonator/PE4 interface did not cause failures,
- d. Large variations in the amount of plasticizer (up to nearly double the specification maximum of about 11%) did not cause failures,
- e. The shock pressure induced in the PE4 from the L2A1 is estimated to be several times greater than the estimated critical shock initiation pressure of PE4,
- f. The test geometry of the PE4 is several times greater than the critical diameter of PE4 to support steady detonation.

6. ACKNOWLEDGEMENTS

We should like to thank members of the 3rd Army Quality Assurance Unit and the Albion Explosives Factory for helpful discussions and the supply of materials for the testing of PE4 and Messrs M.G. Wolfson and J.A. Opalko of MRL for assistance with some of the experiments.

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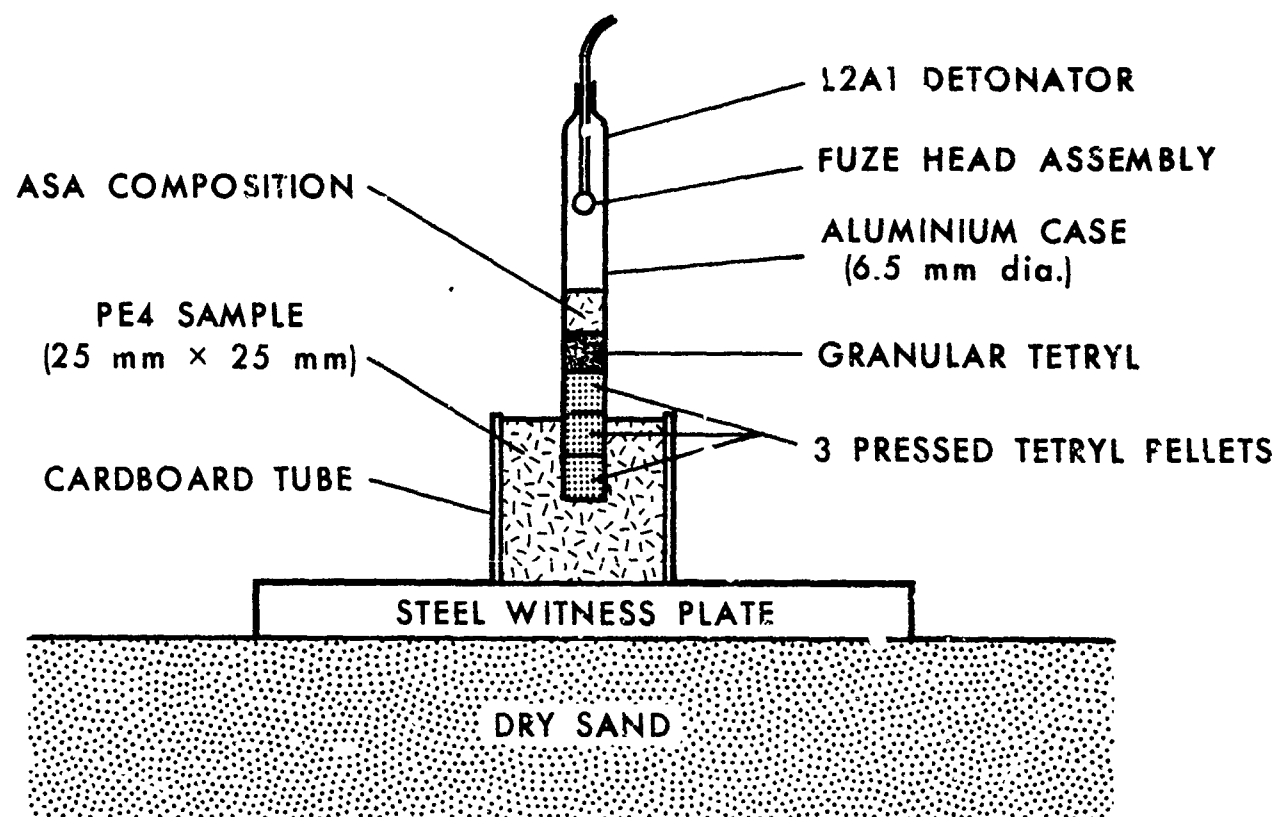


FIGURE 1 PE4 Detonation Proof Test Set-Up

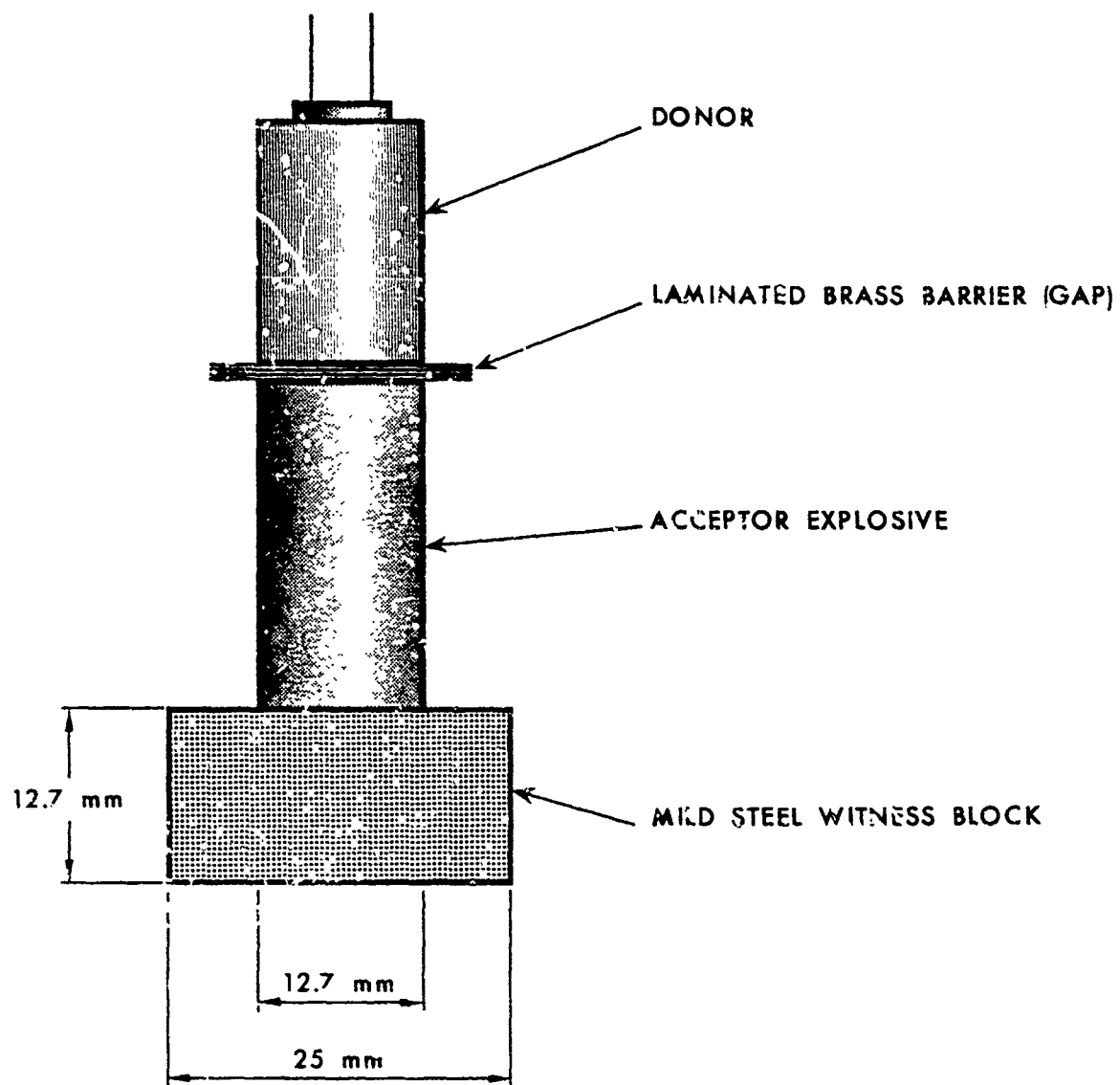


FIGURE 2 The MRI, small scale gap test (SSGT) assembly.

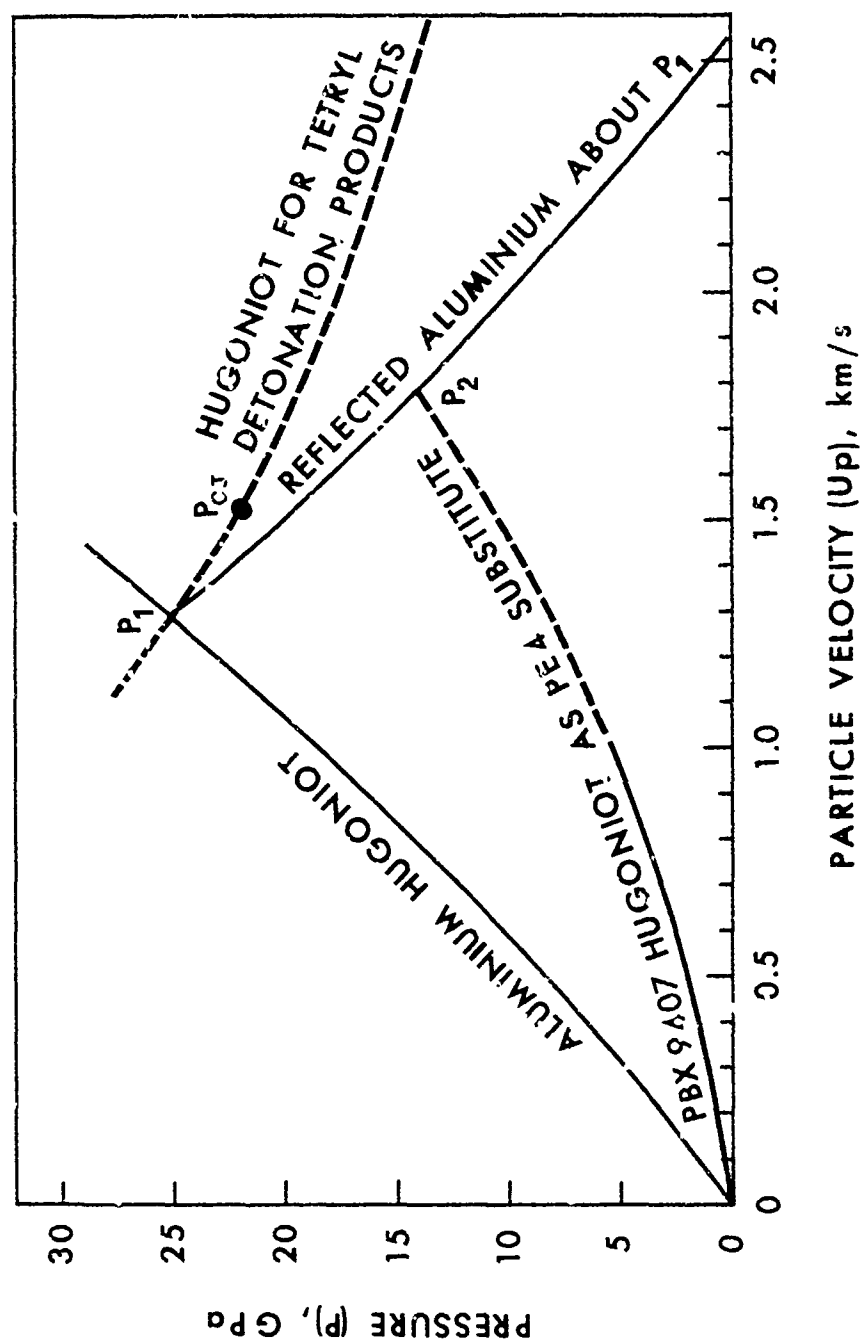
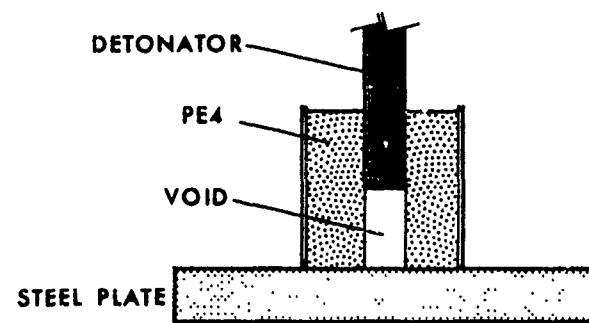
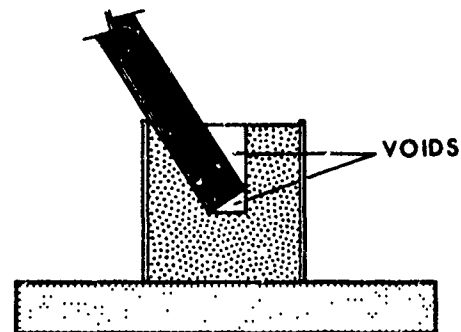


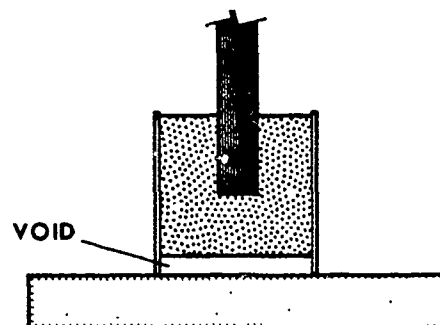
FIGURE 3 Shock impedance matching diagram determining the pressure transmitted from detonating tetryl through aluminium to simulated PE4.



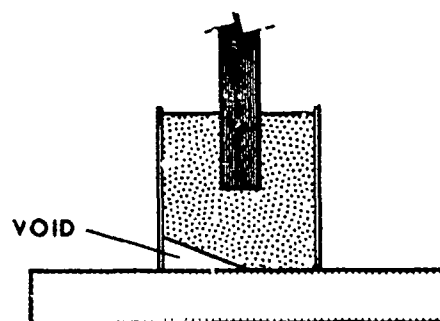
(a) CYLINDRICAL VOID BELOW DETONATOR



(b) VOIDS FROM DISPLACED DETONATOR



(c) REMOVAL OF PE4 ACROSS FULL DIAMETER OF SAMPLE



(d) CORNER VOID

FIGURE 4 Types of Void Examined